Electron theory: Description and analogy

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ELECTRON THEORY

Description and Analogy

*By **J. Robert Oppenheimer***

THE FIRST JOHN FRANKLIN CARLSON LECTURE

We are indebted to Dr. G. C. Danielson, Chairman of the John Franklin Carlson Lecture Fund Committee, for having offered the text of the first Carlson Lecture for publication in these pages. The lectures, which are held in memory of Frank Carlson (1898–1954), professor of physics at Iowa State College, Ames, Iowa, from 1946 until his death, are made possible under a fund established by his friends for the purpose of bringing to Iowa State College each year an outstanding scholar to speak on some aspect of physical science, its philosophical implications, and its relation to human affairs. J. Robert Oppenheimer, Director of the Institute for Advanced Study, Princeton, N. J., gave the present lecture at the Ames campus on May 17, 1955. The second lecture was to have been given last year by John von Neumann, but owing to his fatal illness it had to be cancelled. This year's lecture was given on May 1st by P. W. Bridgman.


John Franklin Carlson

IT is a very special sort of privilege to give this lecture in honor and in memory of Carlson who was, for many of us, both a friend and a colleague. It is certainly appropriate that, as we mourn his loss, we try, as well as we can, to do the kind of thing that he did when he was with us, that he would approve and did approve in his life. It is, of course, also a great pleasure for me to be here in Ames, at a growing and already very famous center of study in many fields, including physics, Carlson's specialty.

Carlson was a student of mine in Berkeley. To those in this audience who are graduate students I would recall the earnestness, the intensity, almost the terror with which he underwent the rites of initiation in a great science, and the seriousness with which he met it. In those days, he used to say, "I have only one wish, and that is to be a good physicist." I think he lived to see that wish abundantly fulfilled. I knew him, I was fortunate to know him, as a colleague when he came back to Berkeley; the two of us had a bit of luck and did some work together that was fun and was successful—something that does not often happen. I knew him in Princeton at the Institute for Advanced Study—a very sweet time.

His interests were extremely broad. He was professionally, primarily, and always a physicist, but his interests in science were catholic. Many of you will know, as I do, the fervor with which he taught men expert in other fields. He loved the history of science; he was interested in philosophy and in literature. He was concerned and sensitive to all human problems, and yet very balanced and unfanatic, a real scholar, one of the most modest of men, a man with a great gift for teaching, whether it was the young fellow whom he would for the first time show a new subject, or whether explaining to rather highbrow characters what he had just found out. He was loyalty itself and great friendliness, and he was very funny. He had a wonderful sense of humor which softened the sobriety, the depth, and the sense of pathos and tragedy with which he looked at human affairs. He exemplified and, with a kind of steadfastness which none of us will forget, he established that being a scientist is harmonious with and continuous with being a man. Being a man of heart, a man of feeling, and a man of knowledge and wisdom, he refuted the notion that if you were a specialist you were inhuman. He established the fact that if you were a good specialist that makes you more human. He did more than any number of symposia or elaborate and sophisticated efforts to provide integration, to give a sense of the unity of human knowledge—because he enjoyed and knew many things from many different fields and, in his person, proved that knowledge was integral and that we were all brothers one with another even when we could not always understand what we were talking about.

He would, I think, have liked the terms of these lectures, he would have liked the thought that a man should come here and tell about physical science and in some way relate it to more general problems, because he believed in such relations. But he was not a shallow man, and he knew that if there are things in the history of physics or in the history of physical science that bear on our lives in other respects, that bear on other aspects of science, that bear on human relations, or knowledge in general, or what is right and wrong, that then this would be a pretty subtle relation, that there was no simple mechanical way in which you could translate what you had learned in physics and make it applicable to the very different problems that you face in daily life or that you face in political life. He would have thought, I think, that human affairs could be illuminated, that they were illuminated, by the experience in the cumulative sciences, in what we call science today; but he would have known that human life was far too broad, deep, subtle, and rich to be exhausted by anything that the scientist would find out in his own field.

Carlson, himself, was an atomic physicist par excellence. He worked during the war on problems of radiation, which were of pressing practical importance, as well as real theoretical interest, in connection with the great establishment at MIT, the Radiation Laboratory. But, when he was on his own, his interests were in atomic physics. It turned out, as always, that the relations between these two fields were formal and full of great analogies and, when he returned to atomic physics, his work was enriched by the experience that he had acquired by studying microwaves, studying how radiation behaves and how you may deal with it mathematically. He worked on the theory of radiation and electrons. He worked on the theory of collisions. I am not going, at this point, to give a scientific vita. It should be known to you that he made contributions with which we are living today, and with which our children will be living, though they may have forgotten how they came about.

The work that he did, with which I was most closely associated, had to do with the subject of the lecture tonight—Electron Theory. I would like to tell the story, or part of the story of this. The reason is that this is a very odd piece of theory indeed. It is an almost perfect theory, in many contexts. It makes it possible for us to predict what we observe with an accuracy of one part in a billion or better than that. It is a theory which is almost closed, almost self-consistent and almost perfect. Yet it has one odd feature: if you try to make it quite perfect, then it is nonsense; and this may have a bit of a moral although I am not going to draw the moral in any great detail.

I would like to tell this as a narrative. I cannot teach electron theory; it is a very hard subject; it is a recondite one. I cannot tell you in detail how one is sure when one looks at the results of an experiment—one is never sure, but how one is convinced—that this experiment means what it says: how, when you see a certain black line on a photographic plate, you know that it was made by an electron; how when you hear a count in a counter, or when you see a constellation of crisscrosses in a photographic film under a microscope, you say, yes, that was an electron that did it. This is part of the cumulative character of science: these things have been learned really over the centuries, and you go to school and you find out what has been learned. You find out that you can use a sort of shorthand. Instead of saying that curve (the set of drops that seems to be distributed along a curved path whose picture you have taken; it was formed in a gas which was supersaturated, which was exposed to cosmic rays) represents a positive electron, you just say, that is a positive electron, or positron. There is a lot of learning in that and I am going to short-circuit it.

I am also going to have to short-circuit the mathematical apparatus which we use, not always successfully, to decide what are the logical consequences of an assertion, what is the content of the theory, because this also is something which people will go to school for many years to learn. So that my description is going to be the kind of thing that you have to do in this world. You have to say, "I will tell you a story about it. I hope you believe me. If you do not believe me I hope you will be interested enough to spend eight years to find out whether I was telling the truth." I know no other way; and I have the conviction that Dr. Carlson himself believed in these efforts to reach out a hand and try to explain across the great gulf of different experience, different language, different interests even, what we were doing, to explain that to each other. But I need to apologize to the many of you in the audience who are professional physicists for lack of detail and rigor, and to the probably rather more in the audience who are not physicists for what may seem the profusion of detail and rigor. I know no way to come around this. I wish I did.

THE electron is one of the fundamental particles of physics. By that we mean only that it has not proven possible, profitable, useful, to regard it as made up of something else. It is only one of a rather large number of such particles. My own count at the moment is 24; but physics is one of those subjects in which you have to have a bit of a theory before you can count, because you do not know what you are identifying until you have a bit of a theory. The electron is the oldest (the first to be found), the best studied, in many ways the simplest particle; it is one of the very few particles which is stable, which does not, that is, of itself, come apart and disappear into something else. It was discovered at about the turn of the century by J. J. Thompson. It is, as you know, the ingredient which gives chemical and most physical properties to ordinary atoms and molecules. It is very light compared to a nucleus, being about 2000 times lighter than the nucleus of hydrogen, the lightest one. It is probably the only particle in nature of which we have much understanding; I have to say that though this is a great deal of understanding, it is far from a complete one.

With Rutherford's discovery of the atomic nucleus, and Bohr's invention, one had the familiar picture (which is not right but which has been so useful): of an atom consisting of a heavy nucleus, quite small (about a thousand times smaller than atomic dimensions), with almost all of the mass and a charge equal to the atomic number. Around this nucleus is a constellation of electrons which Bohr rather cautiously said were in a certain set of stationary states and which he pictured even rather more cautiously in terms of elliptical orbits. These orbits being very large compared to the nucleus, their properties determine the chemistry and the ordinary physics of matter.

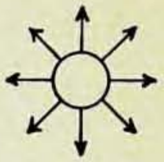
Things were not, however, quite simple, because at the time of the electron's discovery there were two basic theories into which to fit the electron's behavior. One was Newton's mechanics, which said that a particle moved so that the mass times the acceleration was equal to the force; and the force on the electron was the electric force which acted directly on its charge, and the magnetic force which acted if it were in motion. And the other theory was that of Maxwell; which describes how electric and magnetic fields are produced. They are produced by charges and they propagate with the velocity of light; Maxwell in his famous equations said just how that was. So you had a theory that told you how charge produces an electric field and how an electron should move in that electric field. This was all fine; it had to be most radically modified.

But, even before coming to that modification, I should recall an attempt, associated with Lorentz, to see if one could understand the electron itself in terms of these two theories, Newton's equations of motion and Maxwell's theory about how charges make fields. I will say a word about this, not because we are worried about it today—it is obsolete, it is wrong—but because it illustrates with peculiar and rather elementary vividness something that has happened very recently and that is so hard to explain that I can only say it happened and cannot adequately explain it.

The old idea was this: If you have charge producing field and field acting on charge, is it possible that the electron itself is a structure whose own field explains its existence? That is, the charge is accumulated in this way and the forces that the charge produces keep the electron intact. What else happens, when you have an electron that is moving subject to an external force? It is also charged; it must be producing a field; it will respond to this field. The program then looks like this: You say, "I have an electron and Newton's law tells me that the mass, m, times the acceleration, x'', which is the second time derivative of the coordinate, is equal to the force exerted on it from the outside. $mx'' = F$." Then, you try to ask, what kind of effects will the fact that here is a bit of charge, what kind of effects will that have on the behavior of the electron itself?

Well, you start out and say, "I do not know how big the electron is but let me say it is about that big"

and then let me calculate. Then we find that there are two kinds of effects the field makes. One is the building up of all the electric fields around here.



This gives energy and therefore inertia and mass to the electron and you think you may be able to calculate this out.

In the second place, we notice also that when the electron is subject to nonuniform motion, then the fields are altered and new forces are introduced which depend on the motion. All of this, in general, depends on the structure, and—as in some respects we shall rediscover later—we find that as we make the electron smaller and smaller, the energy of the field grows larger, and the mass becomes infinite. The effect of the complicated motion of the electron becomes simple and turns out to be independent of the dimensions of the electron; all structure dependent effects vanish. This equation, $mx'' = F$, becomes complicated by the addition of a term depending on the third derivative of x. The complete equation is

$$-\frac{2}{3}\frac{x'''e^2}{c^3} + mx'' = F$$

where e is the electron's charge, and c the velocity of light.

Well, the physicists of this day (and this is a half century ago) said, "The mass of the electron is known. It is not infinite. I will put in the right mass." This is the term $-\frac{2}{3}x'''e^2/c^3$ which seems to be truly independent of how this charge is distributed, if the distribution is small enough. This has the effect of slowing up an electron which is accelerated. It turns out to have just the effect of taking away from the motion of the electron the energy which the electron must radiate when it is in agitated motion, as an electron in any radio antenna behaves. Now the only point that I want to make about this equation—and believe me, though it may look complicated, it is easy compared to what is coming—the only point that I want to make is the following: If you forget this term, then there are solutions which tell you that if there is a force, the object is accelerated; and, if there is no force, then the only solution is a straight line motion; this is what Newton said. If there is no force acting, the body should move in a straight line, and the electron does that. If you put this term $-\frac{2}{3}x'''e^2/c^3$ in as a correction, there is no correction, because the third derivative of the coordinate is zero for a body moving in a straight line. That is correct. But if you get smart and say, "I can solve this equation," then there are solutions of the form,

$$x = x_0 \exp(t/T).$$

So that means an electron will exponentially accelerate itself; T equals $2e^2/3mc^3$. It is a very short time, about 10^{-23} seconds.

People have coped with this paradox in a variety of ways, but the obvious answer is that that equation was not meant to be treated that way. If you treat this term as a correction, it never does you any harm; it is small for most motions and it agrees with experiment when you try it out. But if you take it completely seriously you get an answer which permits a kind of motion that does not appear in real life. This is a first sign of the fact that the theory of the electron works only when you regard the charge on the electron as it is in fact, as a rather small quantity. I should just point out that the denominator, T, is proportional to e^2, and I will show you another one like that later.

In order to get on at all with the theory of the electron, great reforms had to be made, and were made, in Newtonian-Maxwellian physics. The first of these was the special theory of relativity which, starting with the idea that signals cannot be transmitted faster than light, redefined the notion of simultaneity and the measurements of interval of space and time; showed that a moving object does its stuff more slowly than an object at rest, merely by virtue of being in motion; showed that the mass of a body, the inertia of a body, increased with its energy content and so led to the $E = mc^2$ of Einstein; showed that the definitions of simultaneity, length, and interval all depend on relative uniform motion; and established the fact that the phenomena of nature are the same in (are uninfluenced by) uniform motion, that they will be the same irrespective of whether you see something in uniform motion or not. The theory of relativity took over from Newton most of his laws of motion, but with some modification.

This is the first of those great conservative traits in electron theory which I want to point out. The most important of Newton's laws—the conservation of momentum, the fact that a body not acted on by a force has its velocity and its momentum preserved, the fact that action and reaction are equal and opposite—these were not altered by the special theory of relativity. Only the connection between the acceleration and the velocity, only the relations between mass and velocity, were altered.

That was one great change in the earlier years of the century. The other is harder to describe briefly. It is much deeper; it is very important. This second great change was the discovery of the true nature of atomic mechanics, a discovery which, in some ways, shattered both the Newtonian and Maxwellian framework very much more deeply than relativity. This was the discovery both of the quantum of action and the place of the quantum in the description of atomic systems. The history is a very long one; but we can summarize it by reminding you that it was a resolution of the dual character of light: the character of light as a wave motion, as Maxwell said it was and as we know from everyday experience, with interference on the radio and all the rest of it; and the character of light as always involving a corpuscular discrete exchange of energy and momentum between light and matter in phenomena where they interact.

EINSTEIN discovered the light quanta in the same year that he discovered the special theory of relativity; and twenty years later a way of reconciling this duality was made, not only for light, but for all objects, for all matter, for electrons, for everything else. It is a very practical thing, the wave character of the electron. It is not only necessary for understanding atoms, but it is directly related to the kind of bonding that occurs in organic molecules which seems to us so inescapable a precondition for life itself. The wave character of the proton is what enables it to get into nuclei in the sun and in the other stars and keeps them shining. The wave character of the neutron is what makes it possible to build reactors with materials available on earth and have them react. This pervades all of nature as we know it.

Perhaps the simplest way to summarize what this revolution was, is to say that on the one hand it established a relation between the dynamical description of objects, an electron you may think of, and the waves associated with them. If you have any body—it might be a house, but it should not be because it would not be very interesting, but an electron is a good example—if you have anything and it has an energy content E, then this would be related to the frequency, ν, of the wave representing the situation by the relation of $E = h\nu$, where h is Planck's constant; and, if the momentum is P, that will be related to the wave number, K, of the wave by this simple relation, $P = hK$, where again h is Planck's constant. So you have a code of translation from the description in terms of particles to the description in terms of waves.

This code leads to a very basic point: there are a variety of ways of exploring and objectifying the state of an electron in nature and some of them are exclusive of others. An attempt to make a wave which is very much localized (therefore to know that the electron is in a small region of space) will interfere with the use of limited ranges of wave numbers or momenta. Formally one gets that the lack of definition in the coordinate of an electron Δx, and the lack of definition of momentum ΔP, have a product which cannot be smaller than this constant h.

$$\Delta x \Delta P \geqslant h.$$

The equation concerning energy we shall need to use later. We may say that in a time interval, Δt, the energy of a system cannot be defined better than is given by this relation:

$$\Delta t \Delta E \geqslant h.$$

If you want a definition of energy better than this ΔE you must take the time longer than this Δt.

This is a very rough way of talking about the wave mechanics, but it must suffice to get us on. I need to remind you that on the basis of a little bit of relativity and a lot of atomic mechanics most of the physical and chemical properties of ordinary matter and a great deal of the properties of nuclei too (composed of neutrons and protons), have found an orderly explanation—not always a complete one, because things can be too complicated to work out, but one which we believe is, in principle, adequate. So that the whole of physics for the last 30 years has been directed towards questions more or less exclusively evoked by doing abnormal things with matter rather than by simply observing its normal behavior.

And how is that? It is many different things. But, for one thing, these relations $\Delta x \Delta P \geqslant h$ and $\Delta t \Delta E \geqslant h$, and Einstein's relation $E = mc^2$, together give you another code of translation; and that code says that there is a relation between length and time on the one hand and energy and momentum on the other. A time can be connected with an energy by the relation $T = h/E$, and with a mass by the relation $T = h/E = h/mc^2$. A length can be connected with a mass by the relation $L = h/P = h/mc$. And what that means is that if you wish to study the finer structure, in space or in time, of matter, you will be led to use very high energy or very massive particles. But, if you wish to study very massive particles, you will need a lot of energy; if you want to explore smaller and smaller regions of space, you will have high energies to deal with. And this is, of course, the reason for the overwhelming importance of accelerators and cosmic rays in this aspect of the progress of physics.

In all of this development of atomic mechanics, there has been a trait of conservatism and a use of the idea of analogy similar to those that I mentioned in relativity. Things like these—limits on the accuracy with which you can define position or momentum of particles, dualisms between waves and particles and so on—sound very radical. But, throughout, there has been first a principle and then a discovery that in all situations in which it is all right to use a picture of waves, the Maxwellian description of these waves (or whatever one had in classical physics) shall not be monkeyed with. It is right. Wherever it is right to use a Newtonian picture of an orbit, that orbit will be followed. It is only when one has a situation where these ideas do not apply that one cannot use the classical formal laws. And it is true that all the laws of quantum theory, esthetically and in symbols, are very much like the classical laws that they supersede. This trait of conservatism, this use of analogy, is what has made atomic physics so rapidly a success. It is a revolutionary business; I am not playing that down; but it is only revolutionary at one point. It is revolutionary only at this point regarding the duality of waves and particles. It takes everything else more or less as it finds it and preserves it, and it has led to some really astonishing successes.

The question, then, is what happens when you take this new machine, the quantum theory, the wave particle duality on the one hand and relativity on the other, and you put some of the old questions about the electron itself. You think that you would like to understand the motion of electrons in external fields; you would like to understand their behavior; you would like to understand how they emit radiation and all the rest of it. That is the electron theory, which has come to be a great success, and of which I wanted to talk.

There are two basic processes. They do not always occur, but given the right circumstances they will occur. One of them is very familiar and one of them is very unfamiliar. The familiar process is that by which an electron, if it is not moving uniformly, will give out some radiation. This is what happens to electrons in antennae when you get radio waves; it is what happens when electrons are stopped by the electric fields surrounding the nuclei in the target of an x-ray tube, and you get the x-rays from it; it is a very well studied thing. I just have to indicate that there is something (F) to accelerate the electron (e) or change its motion in order to give the γ-ray (γ)

$$F + e \rightarrow \gamma \text{ (Process 1).}$$

This is different from the electrodynamics of 1900 only in that we know that these γ-rays have their corpuscular property, and some of the detailed rules for the rate at which this process happens correspondingly change.

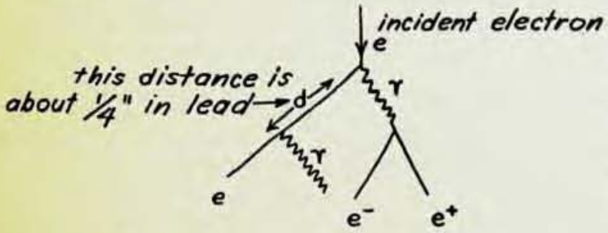
The other process was really a new one when it was discovered twenty years ago; it is typical of the wave character of electrons that it should occur. In this process, we have a γ-ray plus some kind of electromagnetic field. They do something that was not anticipated. They produce two things, an electron and a positive electron or positron. The two are called a pair.

$$\gamma + F \rightarrow e^- + e^+ \text{ (Process 2).}$$

These particles (electron and positron) are identical except in the sign of their charge. The fact that the laws of physics should allow a positive electron is not new; that is true of classical physics as it is of the physics of this century. The fact that this will happen, this materialization process, is a pretty direct consequence of rather general things, of relativity, and of the wave particle duality of quantum theory. I know of no description which satisfies the requirements that nothing travels faster than light, which satisfies the rules of the quantum theory, and which has in it light and electrons that does not make this process a necessary thing. It has not been proved that no such theory exists, because that would be a kind of hard thing to prove, but I have never seen one and it has been tried for a long time to devise one. This pair production was a theoretical prediction which the theorists who made it were somewhat reluctant to believe until the positive electron was discovered. It was discovered in the cosmic rays by Anderson and immediately gave an immense stimulus to electron theory.

These two processes, as they occur in nature, give rise to one of the phenomena which Carlson studied with success and great interest. The cosmic rays are many things: they have a mysterious origin, and they are interesting for all sorts of reasons; but a very great part of their interest is that they are a wonderful source of radiation of high energy, energy which may go up to a hundred thousand times, or even a million times, the energies now available in accelerators and may go even higher than that. So that if a phenomenon depends on having a lot of energy available, the cosmic rays are a good place to look for it.

Now let us see what happens if we have an electron and it comes somewhere near the nucleus of an atom where there are strong electric fields. It will be accelerated, and in the course of that it will give off a γ-ray, and then the electron will go on with a little less energy. But now if the γ-ray comes near the nucleus of another atom it will make a pair, an electron and positron pair; and one of these may come near another atom and give off another γ-ray.



Carlson and I worked on this a little and found that this distance d is not very long. On the average it is about a quarter of an inch of lead, something like that, or only about a foot of water. Not very big distances are involved. These multiplicative processes were found in cosmic rays. In fact they had been there all along. One was shy about saying what they were. They are really impressive. The very high-energy ones spread in the air. There may be at one time a million of these things in one event. They may cover a part of a square mile in distance while building up this enormous multiplicative event which is called a cascade or shower. And this is a kind of vivid demonstration of the elementary action of the radiation of light (γ-rays) by an electron, and the conversion of light into electron pairs, one after the other, in different events.

Part of the importance of this finding of Carlson's was that one saw these cascades in the cosmic rays and was sure that this was largely a correct theory. Carlson had worried a good deal about whether the quantum theory of electrons in radiation was correct at all, because in the cosmic rays there are many particles that do not radiate. They just go straight along and do not multiply at all; they penetrate through lots of lead. There are other particles that do quite different things. So very grave doubt was cast on the correctness of these theoretical ideas. But our doubts were largely resolved (and since have been even more resolved) when we saw that there were things that behaved just this way and really quantitatively just this way.

One of the important points, then, is that because of that certitude and because, in the cosmic rays, there were things which did not behave this way, which did not multiply, which did not give cascades, one knew that there were other particles in the cosmic rays than the familiar ingredients of matter. And that started a search and a period of discovery which has been accelerating and has been of most extraordinary vigor in the last years; so that, at the moment, we have some two dozen elementary particles, most of them radioactive and unstable, all of them transmuting one into the other when they collide, though not without some inhibitions. They all transmute into something, but they do not all transmute into everything. These discoveries appear to be taking us very close indeed to the elements of the subatomic world, to the actual atoms of which matter is made. This development is one of the byproducts of the theory of cascade showers. Some of these objects, not electrons, are quite inert and are connected with electrons only by incredibly weak forces so that transitions occur very slowly indeed. Most of them, on the other hand, have very strong interactions with each other, which make the transitions occur rapidly and make their production and their destruction very common events. There are forces in nature enormously weaker than electric forces and there are forces very much stronger than electric forces. Electric forces and electron theory appear to occupy a middle ground.

THE success of the theory of the electron, basing itself on these elementary reactions, with a quantitative and relatively straightforward way of describing how often and under what conditions they happen, led to at least two attempts at an analogous theory. One was Fermi's theory to describe the radioactivity of nucleons. The simplest example, though it was not originally an example, is that the neutron is radioactive. It produces a proton, an electron, and another little object which is called a neutrino and is hard to find. Fermi made the theory of this in exact analogy to the transition of an electron from one state to another, electrons being accelerated and in the process a γ-ray appearing. Instead of the process

$$e_{\text{state 1}} \rightarrow e_{\text{state 2}} + \gamma,$$

he said a neutron goes into a proton and in the process an electron plus a neutrino appears:

$$N \rightarrow P + (e + \nu).$$

He initially made the theory formally very similar. It turned out, with rather minor modifications, that this gives a powerful and helpful description of the phenomena of radioactivity; its connection with many other problems in physics has remained an indigestible question.

The Japanese physicist Yukawa made an even more daring and, as we shall see, not so totally successful analogy to electron theory. He said, "There are these strong forces, which hold nuclear matter together, forces from neutrons interacting with protons, neutrons with neutrons and so on. They are very strong; they have very short range and, when momentum goes from one particle to the other, this very often involves an exchange of charge between one particle and the other." He said, "I know that if this were electrodynamics there would be a field of force stretching from one electron to the other. This field would correspond to the wave aspect of light quanta which go from one electron to the other. The quanta that go from one nucleon to another may be charged and that would account for this phenomenon of charge exchange. If they were heavy, that would explain the fact that nuclear forces do not act over a big distance but have a range." Thus, he would point to the formula $\Delta t \Delta E \geqslant h$, and he would say that an object of mass M has an energy Mc^2 and can last a time certainly not greater than h/Mc^2, because that is the uncertainty relation. It can travel certainly no greater distance than hc/Mc^2. Then

$$R = hc/Mc^2 = h/Mc$$

should be the relation between the range (R) of the forces and the mass of the particles that are associated with the field. He did say this, and he said a few more things, and some very great truths have been in this theory; it has occupied physicists for a long time. In this complex analogy that Yukawa made between the forces between nucleons due to these new particles (which are called mesons) and the forces between electrons due to light quanta, Yukawa was trying to keep the theories formally as similar as possible.

But before one can really get into that, we had better say a few words about some of the things that have happened to electron theory. Because, as of the turn of the century, it was not free of some contradictions and some troubles. If an electron can emit γ-radiation, then, when an electron is just standing around, it will not free that γ-radiation because there is no source for the energy. It is not accelerated or anything. But it will emit γ-radiation and then reabsorb it, and the time will just be about h times the reciprocal of the energy of the γ-ray. If a γ-ray can make pairs, it will not do so when it is just traveling through free space and there is nothing for it to hit. But part of the time it will exist in the form, not of a γ-ray but of a pair of electrons, electron and positron. Those electrons, in turn, will sometimes be accompanied by secondary γ-rays and those γ-rays sometimes in turn by secondary pairs. This sounds terrible; but fortunately each step in the process is less and less probable and by about a factor of 1000, because the number, e^2/hc, which measures the relative probability of these various steps in the sequence, is about one-thousandth. That means that it is only one-thousandth as probable that you find two γ-rays around an electron as that you find one, and it is only a thousandth as probable that you will find one as you find none.

Still, these complications have two kinds of consequences. One is that, if you want to talk about the real world, you ought to talk about the electron with its family, all its γ-rays and pairs and all the rest, and ask what they do. And this turned out to be very important since the family changes the properties of the electrons a little. It changes its magnetic properties and changes the energy levels of the simplest systems; such as hydrogen (an electron in the field of a proton) or positronium (the system made up of one positive and one negative electron, twice the size of the hydrogen atom, behaving very much like the hydrogen atom). These changes were discovered experimentally in the years after the war, and are just a description of the altered character of the electron because of these virtual cascades that go on all the time. So it is also with light. The properties of light itself in the free world, when it is all by itself, are not altered; but the properties of light in its interaction with matter, with charges, the properties of light which make it shake off pairs when two light quanta collide, are altered. This is one reason for wanting to give a description of these interactions. The changes are, of course, small because the charge is small.

The other reason is the following: we had made electron theory for a long time but we had always been rather careful not to make it too well. We had calculated how often something would happen and we had done it roughly, and then we had not made corrections for all these complications that I have just outlined. The reason we did not make corrections is that each correction, though it had a small coefficient (e^2/hc), also had a large coefficient which was multiplied into it and which was, in general, infinite. It was infinite, because, although the effects of γ-rays on electrons and of electrons on γ-rays are small for any given γ-ray, if you go to γ-rays of infinitely high frequency, if you consider more and more small-scale disturbances, these effects add up and accumulate to an infinite amount.

A discovery was made about eight years ago, a very beautiful one. It was this: there are two kinds of phenomena; the kind of phenomena which depend in a sensitive way on the behavior of electrons and γ-rays for arbitrarily high frequency, arbitrarily small space-time phenomena; and those which are relatively insensitive. The only two which depend on the high-frequency behavior, which is the root behavior in the very small spaces, very short times, are the charge of the electron and its mass; and these are the things that are infinitely affected by those phenomena, very much as in the classical theory of Lorentz. And physicists then said, "Good, we will give up this attempt. We cannot calculate the mass of the electron. It would be meaningless anyway in a theory in which there are no other particles, because we could give meaning only to its ratio to the mass of something else. We would like to calculate the charge; we would like to calculate that number one in a thousand; but we will give that up too. These things we will measure; then everything else will be given by the theory in a finite way." So they said; and this is what is called the renormalization program. It has the double purpose of translating from a description of an electron with none of its cloud and company of γ-rays and electrons around it to the description of the electron as it really is, and to do the same for the γ-ray; and, at the same time, of removing from the description those features (namely, the mass and charge) which would come out infinite and which are nonsensical.

A basic idea behind renormalization is that electrodynamics cannot be the whole story. But if you try instead to modify electrodynamics in other ways (and it has been tried many different times and many different ways), to say that for very small regions of space and time things will be different, it is very hard to make such a modification (lacking any real knowledge of the physics of that region) which is even formally consistent with the requirements of good sense, of causality, of the continued existence of matter, of complementarity, and the rest of it.

The renormalized theory has been very successful. It is the theory which has made it possible to predict the levels of hydrogen to a part in ten billion, to do very well with the spectrum of positronium, and to give a very accurate account of phenomena at ordinary energies. The reason for the success is that one can do the corrections for the additional electrons and γ-rays, step by step, expanding always to take more and more complicated situations; and each step is much smaller than the one that came before, maybe some hundred times smaller.

At very very high energies this convergence is not so good any more and that has been known a long time. People have had the curiosity, the morbidity, to ask, "Well, suppose that I do not do this step by step, suppose I try to do the whole thing. I might like to do that because, if I could get rid of this expansion, I might even get some insight into the value of the constant, e^2/hc. I could say how things would behave even if it were a large constant." And there a very odd thing has turned up. It has turned out that for ordinary phenomena one can probably get things accurate to one part in ten to the fiftieth or something like that, and at energies as high as the highest cosmic-ray energies one still is almost certainly making no appreciable mistake in the discussion of electrodynamic things with electron theory. Nevertheless, if one tries to do it just a little bit better and get it exact, and get it so that it holds at all energies, then the theory seems to turn out to have no meaning whatever.

In fact, in all efforts so far, it predicts something like this: that the electron should have another state, another configuration with a mass which is negative and is enormously negative,

$$m' \sim -m \exp(hc/2e^2).$$

The exponent is about five hundred; you might say that sounds pretty bad. But it is not only that the mass is negative and enormous—this alone would be bothersome; but whenever this state occurs, it occurs in such a way that, if something goes into that state, it increases the probability of things going into other states. So we are producing more and more electrons and more and more phenomena whenever we have a collision or whenever anything occurs. This is just another way of saying utter nonsense; it is utter nonsense of rather the same kind that we ran into with the Lorentz theory (and the Dirac modification of the Lorentz theory) of an electron. One has pushed the theory too far. One has pushed it to the point where it is saying to us, "I am not logically consistent.* You have left out something and that has made a hole in me, which I show, although I cannot say what belongs in the hole."

What belongs in the hole, of course, is all the rest of the world. It is those weak interactions which occur in β decay, it is those strong interactions, and those 24 different kinds of particles which may some day be 30 or 40 or even an infinite number, which appear in the great laboratory of the cosmic rays. It is all the rest of physics, which is not very closely tied in, and which leaves electrodynamics and electron theory an almost perfect, but not a perfect subject.

The analogies, especially Yukawa's analogy, have not fared so well. The reason is not because his quanta have a mass and his quanta have a charge. The primary reason is that his analogue of the number e^2/hc is not small at all but very large; and therefore, in this situation, the nucleon is very often accompanied, not by one meson but by several. These things cannot be treated as corrections; and the fact that they cannot be summed, that one cannot treat them in any other way than as corrections, means that one does not have in a strict sense much of a theory at all. However, it has been possible, with a good deal of sophistication, to use this analogy, together with a good deal of experimental information, to coordinate phenomena of scattering, of meson production, and of nuclear interactions—those phenomena which occur for mesons of rather low energy (comparable with the meson rest energy μc^2) and those phenomena which have to do with internuclear forces at rather large distances (comparable with the meson Compton wavelength, $h/\mu c$).

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* "The question of the consistency of electrodynamics, or perhaps more realistically, the nature of the inconsistency of electrodynamics, has continued to occupy attention during the past two years. It is not definitely or rigorously settled. (Ref: Källen, G., 'On the Mathematical Consistency of Quantum Electrodynamics', *Proceedings of the CERN Symposium*, 1956, Vol. 2)." J. R. O., Princeton, N. J., April, 1957.

This is a first and a very modest step in the beginnings of sorting out the new physics. These 24 particles are there, and, as I said, there are perhaps more. They have very odd properties. They were wholly unexpected. The theory of Yukawa, which was supposed to tie together a few of them—certain mesons and the nucleons—would, if it were true, cover only a very small subsection of the field. It does not cover that except in a more and more limited area. This subsection is not separate from the rest of the field as electron theory is from most things. It is clear that we are in for one of the very difficult, probably very heroic, and at least thoroughly unpredictable revolutions in physical understanding and physical theory. One of the great times in physics lies ahead; it is certainly something that will often make us remember how much we miss the guidance and the companionship that Carlson could have given us had he lived.

THROUGH all of this story there has gone a theme of the use of analogy in building physical theory: the analogy between Newton's laws and the laws of relativity, the analogy between Newton's laws and the laws of atomic physics, the analogy between Maxwell's waves and the waves of quantum physics, the analogy between Fermi's theory of β decay and the quantum theory of radiation, between Yukawa's theory of mesons and nuclear forces and the quantum theory of the electron.

Over and over again, we have used formal analogies. This is not strange. We are trying always to feel our way into something new and unexperienced. We take into it what we have, which is our own experience, in this case of the physical world, and we seek a relevant pattern of form and order. Number plays a part in the expression of this, but is not essential to it; the notion of analogy is deeper than the notion of formulae, though not deeper perhaps than all parts of mathematics. These analogies are sometimes right and sometimes wrong. Analysis, the confrontation of the full logical consequences of what it is that we have asserted with what we have learned to observe, is the final arbiter of whether the analogy is right and how far it is right. It determines the truth of the conjecture. But, without the analogy, there would be no conjecture, no way to go into a new field.

You have, in entering novelty, to use what you know. You would not be able to make meaningful mistakes without analogy. You would not be able to try things out, the failure of which was interesting. You start thinking by the use of analogy. Analogy is not the criterion of truth; it is an instrument of creation, and the sign of the effort of human minds to cope with something novel, something fresh, something unexpected. Analogies play, in the relation between sciences, a very great part, sometimes a harmful one; and they also play a decisive part in what little there is that natural science can teach of general use in general human experience.

One of the great things of this century is how illuminating and relevant the experience of the quantum theory, of complementarity, has been; how wide the scope of those analogies; I think for our children it will be better understood. What am I speaking of? The uncertainty in the position of an electron can be very small, the uncertainty in its momentum can be very small, but no experiment, no situation, can be devised which makes them both very small at the same time. This means that the physicist, or anybody else, has some choice as to what he is going to look at in a system, what he is going to realize. Is he going to realize a positioned electron or an electron which has a well defined velocity and wavelength? He can do one or the other but they are complementary in the sense that there is no piece of equipment which will do both for him. He cannot realize them both together; one says that they are complementary situations.

But life is full of that, of course. We all know it in the relations between our acts and our introspection, our thinking about our acts. Hamlet has said it better than Planck's constant. We know it in the difference between, in the inherent inability fully to combine, the ideals of love and the ideals of justice. They are just about two different things; balance between them, yes, but fulfillment of both simultaneously, I think we know that that is not possible. We know it in the difference between a piece of knowledge, a piece of equipment, or a man regarded on the one hand as an instrument and on the other hand as an end or a purpose or an object; the difference between the inevitable and universal transcience of events and their eternal and timeless quality. This is part of life; and it is simply a rich set of analogies to the rather sharply defined, nonambiguous, straightforward complementarity that one found in the heart of the atom.

So it is I think, also, for the electron theory. All of life has both its aspects, being complete in itself and referring outside itself. Closure and openness are with us all the time. Here is this quite beautiful theory, perhaps one of the most perfect, most accurate, and most lovely that man has discovered. We have external proof, but above all internal proof, that it has only a finite range, that it does not describe everything that it pretends to describe. The range is enormous, but internally the theory is telling us, "Do not take me absolutely or seriously. I have some relation to a world that you are not talking about when you are talking about me." This is a kind of rebuke, of course, to anyone who believes that any specialty can wholly exhaust life or its meaning.

Our knowledge is limited by the limits of our experience. It grows all the time. As we see more of the harmony, the order, and the beauty in the world, we take great pride in sharing that knowledge. This knowledge is the reward of the scientists. The power that comes with it is for other people. But we can be reminded, at the same time that we are aware of our knowledge and its scope and its beauty, that built into it there are also these perceived limitations. I think that is a lesson that Frank Carlson never had to learn, because he was a very modest man.